HYDRODYNAMICS OF A SHIP WHILE ENTERING A LOCK

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SUMMARY

The hydrodynamics of a ship that are associated with lock entry are described empirically and mathematically. Emphasis is put on the generated translation waves. The six-waves-model of A. Vrijburcht is used to calculate the wave system in the lock. These calculations are compared with empirical data and the six-waves-model is improved in a theoretical and empirical manner. The most significant adjustments to the model are the introduction of speed-dependency, taking account of the ship's hull shape and of the layout of the lock entrance. The model is compared to experimental results with scale models of a bulk carrier and a container carrier.

NOMENCLATURE

a	acceleration of the ship (m/s²)
h_1	wave height of wave 1, original wave, between the bow of the ship and the end of the lock (m)
h_2	wave height of wave 2, reflected wave between the bow of the ship and the end of the lock (m)
h_3	wave height of wave 3, transmitted wave between the entrance of the lock and the bow of the ship (m)
h_4	wave height of wave 4, reflected wave between the bow of the ship and the end of the lock (m)
h_5	wave height of wave 5, reflected wave between the entrance of the lock and the bow of the ship (m)
h_6	wave height of wave 6, original wave from the entranceof the lock towards the canal (m)
m'	total (virtual) mass (kg)
v	speed of the ship (m/s)
x_{ship}	position of the ship's bow (m)
z_k	water level depression alongside the ship due to sailing in the canal (m)
z_n	additional water level depression between the bow of the ship and the lock entrance (m)
z_v	translation wave height generated due to the lock entrance (m)
Δz_v	additional translation wave height generated at one time-step due to the lock entrance (m)
T	total thrust (propeller thrust + tug force) (N)
F_x	hydrodynamic forces (N)
F_f	resistance forces (N)

1. INTRODUCTION

In the most recent decades, maritime transportation has experienced an increasing importance due to an ever more globalising world. Larger vessels have been constructed and access channels, port infrastructure and locks have to follow that evolution. A number of locks have been under consideration or construction in recent years and a further exploitation of existing locks is examined. The growing number of large vessels can only be used if sufficient infrastructure, like locks, is available.

Especially for large vessels that are most critical, the hydrodynamic phenomena induced by a lock entry are important, since the ship's movements are strongly influenced by those phenomena. Reliable research tools are necessary. Most commonly, they consist of a combination of model tests, simulations and full-scale measurements. Reliable simulations with experienced pilots offer an economical way to test infrastructure. The main objective of this study is the improvement of mathematical simulation models, dedicated to the lock entry. The hydrodynamic effects are examined empirically and calculated with the improved mathematical model based on Vrijburcht [1].

This paper is based on a master's thesis with the same title and written by the first author [4]. Some additional calculations have been carried out since the completion of the master's thesis, which are described here.

2. EMPIRICAL STUDY

Lock entrances are investigated empirically in two ways: real-scale measurements and model tests. A large number of tests with self-propelled ship models have been carried out by Flanders Hydraulics Research for the Panama Canal Third set of Locks and West lock Terneuzen [2][3]. A selection of model tests has been considered in this article. A 12000 TEU container carrier is used for the Panama Canal Third set of Locks at a 1/80 scale. For

West lock Terneuzen a bulk carrier model at scale 1/60.6 is used.

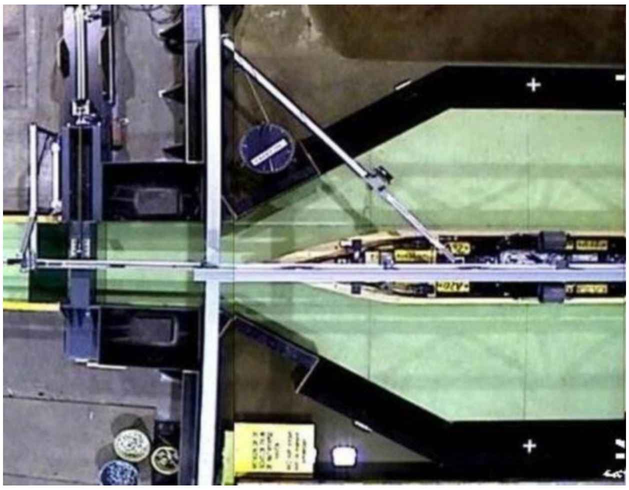

Figure 1: Top view of a model test with a container carrier scale model for the Third Set of Locks in the Panama Canal (Flanders Hydraulics Research)

The contraction of the wet section at the lock entrance has an important influence on the hydrodynamic effects. Translation waves are generated at the bow, travelling into the lock which causes an increase of the water level. Ships causing a higher blockage of the lock and entering at higher speed induce higher translation waves.

There are important differences between the empirical results for tests with full ships compared to slender ships. Those are described briefly hereafter.

3.1 EFFECTS OF A LOCK ENTRY BY BULK CARRIERS

During the scale model tests, several parameters were measured. The most important parameter that is used for the interpretation of the effects during lock entry is the water level elevation at the end of the lock. By measuring the changes of the water level, the generated translation wave can be observed directly. A typical graph of the wave height due to a bulk carrier scale model is given in figure 2.

If a bulk carrier approaches a lock, an increase of the water level is observed at the end of the lock. The increase occurs before the ship reaches the lock entrance. The approach towards the lock entrance, as can be observed in figure 1, is such that the wet surface contracts over a certain length. This has a clear influence on the generation of the translation waves.

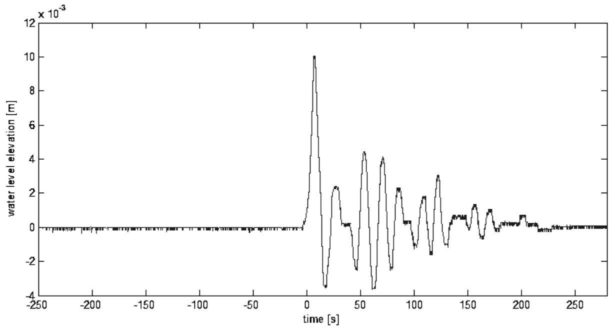

Figure 2: Measured water level elevation at the end of the lock for a bulk carrier (15% UKC). The approach speed is equal to 0.152 m/s.

After the initial increase of the water level, a strong and regular oscillation of the water level can be observed. The amplitude of the oscillating wave height decreases over time. Some abnormalities can be observed on the second, fifth, eighth and so on, oscillation. The wave seems to be 'topped-off'. No decisive explanation for this phenomenon was reached during the current study, but it seems to be influenced by the testing infrastructure: a closed basin where long waves can develop due to the initial acceleration of the ship and are reflected at both ends of the basin.

Table 1: Main dimensions scale model tests

Main dimension lock (scale model)	
Lock width	0.66m
Lock length	6.25m
Water height	variable
Main dimensions bulk carrier (scale model)	
Ship beam	0.63m
Ship length over all	3.82m
Draught	0.24m
Main dimensions container carrier (scale model)	
Ship beam	0.61m
Ship length over all	4.56m
Draught	0.19m

3.2 EFFECTS OF A LOCK ENTRY BY CONTAINER CARRIERS

In figure 3, the wave at the end of the lock is given for the two test cases of the Open model test given in [3]. These scale model tests are carried out by Flanders Hydraulics Research for the Panama Canal Authorities.

Container carriers have a more slender hull causing translation waves to be less pronounced than those generated by bulk carriers. The waves are smaller and contrary to the waves generated by bulk carriers, the waves due to container carriers do not oscillate by a regular pattern.

Secondary effects are much more apparent in these cases Irregular changes in the water level can be observed before the ship reaches the lock and even more unexplainable changes are observed during the entering procedure. In both cases the water level falls sharply at 80 seconds and at 50 seconds for the case with 10% and 20% under keel clearance, respectively. This phenomenon is caused by a sharp deceleration of the ship due to propeller action.

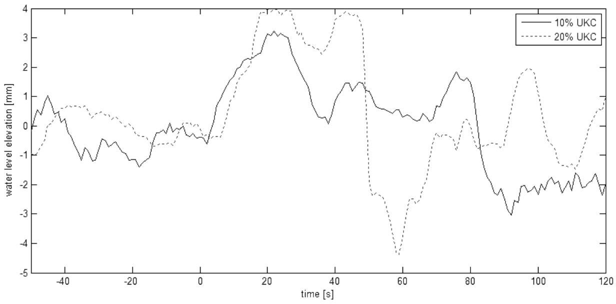

Figure 3: Measured water level elevation at the end of the lock for container carriers (10% and 20% UKC). The approach speed is equal to 0.11 m/s in both cases.

3. MATHEMATICAL MODELING

An accurate and fast calculation of the wave height that is developed during a lock entrance is not a straightforward undertaking. Necessarily, simplifications have to be implemented. For instance, a multi-dimensional approach is not viable at this stage, nor do full 1D shallow water equations (Saint Venant equations) lead to a usable solution. The latter is described in the full text of the master's thesis, but did not lead to solutions.

3.1 ORIGINAL SIX-WAVES-MODEL

The six-waves-model of Vrijburcht [1] is used to calculate the translation waves generated by the lock entry of a push-tow. A 1D approach is used, longitudinal water movements are considered and currents in vertical and cross-directions are neglected. The most important assumptions of the original six-waves-model are: the ship's speed is constant (1), the lock is closed at the end (2), no wave reflections are considered in the canal (3), the ship has a rectangular cross section (4) and the transfer from canal to lock is abrupt (5).

The six-waves-model consists of two steps. First a system of equations of Bernoulli and continuity equations is solved, rendering water level and flow parameters. The most important parameter is z_v, the resulting wave height. Hereafter, this complex system will be called "Vrijburcht's system".

Then the wave height of six waves is calculated over a period of time: $h_1(x,t)$, $h_2(x,t),\dots,h_6(x,t)$. The six waves consist of two initially generated waves, travelling respectively towards the end of the lock and towards the stern of the ship, and four reflected or transmitted waves. The calculation process of the reflections is not changed in this work, emphasis lies on the way the initial wave is generated. In the original six-waves-model, this initial wave is constant and equal to:

$$h_1(x,t) = z_v \tag{1}$$

once it is fully developed.

3.2 IMPROVEMENTS TO THE SIX-WAVES-MODEL

The scope of the original six-waves-model is rather limited. However, it has its merits, namely simplicity and transparency. Therefore, an improvement of this model, maintaining its merits but expanding its scope, would be very desirable. The model is improved by eliminating and compensating a number of assumptions, namely (1), (4) and (5).

3.2 (a) Introduction of a variable calculated speed

The speed of the ship is calculated by Newton's law of motion, considering the propeller thrust and tug force, hydrodynamic forces due to the translation waves and resistance forces due to deceleration losses and frictional resistance:

$$v(t) = v(t-dt) + a(t)\cdot dt \tag{2}$$

The acceleration *a(t)* is calculated with Newton's law of motion:

$$m'\cdot a(t) = T - F_x - F_f \tag{3}$$

With T the propeller thrust (thrust deduction being neglected), F_x the hydrodynamic forces, caused by the generated translation waves and F_f a set of resistance forces due to deceleration losses at the stern on the one hand and due to frictional resistance on the other hand.

The introduction of speed-dependency has two effects: the position of the ship x_{ship} changes, causing changes in the reflection:

$$x_{\text{ship}}(t) = x_{\text{ship}}(t-dt) + v(t)\cdot dt \tag{4}$$

Secondly, the generated wave height at the bow is adjusted according to the ship's speed. The wave height at the bow is assumed to be proportional to the square of the ship's speed:

$$h_1\big(x_{\text{ship}}(t),t\big) = h_1\big(x_{\text{ship}}(t-dt),t-dt\big)\cdot\left(\frac{v(t)}{v(t-dt)}\right)^2 \tag{5}$$

This means that the initial wave changes at the bow at every time-step, and afterwards, the wave travels further down the lock as following:

$$h_1(x,t) = h_1(x - v(t) \cdot dt, t - dt) \qquad (6)$$

The speed-dependency is the first major improvement to the six-waves-model and has a significant influence due to the important deceleration during the entrance.

3.2 (b) Introduction of a realistic ship

The second improvement consists of the introduction of a realistic bow shape. A push-tow is assumed in the original six-waves-model, which causes a sudden contraction of the wet area at the lock entrance. The influences of the bow shape on the translation waves generated by a container carrier and bulk carrier illustrate the importance of a proper bow shape in the mathematical model. Due to a realistic bow shape, the contraction of the wet area at the lock entrance occurs gradually. The bow wave is calculated as the accumulation of waves generated at every time-step due to an increasing width and cross-sectional area of the ship at the lock entrance. This is done by solving the Vrijburcht's system at every time-step for a ship with a width and cross-sectional area equal to the increase of the values at the entrance of the lock over one time-step. The resulting wave height is equal to $\Delta z_v(t)$ and is added to the wave height at the bow of the ship at the appropriate time[1]:

$$h_1\big(x_{\text{ship}}(t), t\big) = h_1\big(x_{\text{ship}}(t - dt), t - dt\big) + \Delta z_v \qquad (7)$$

The lock section that is taken into account is the wet section of the lock at the entrance at the previous time-step. The improvement induces a smoother and more realistic course of the wave height. The wave height is also significantly lower due to a gradual instead of a sudden contraction of the wet surface.

3.2 (c) Introduction of a realistic lock entrance

Thirdly, the narrowing between canal and lock section, which is assumed to be abrupt, is approximated more accurately. The narrowing of the test set-up for the model tests is not sudden. The section narrows over a length which is about 2.8 times the width of the lock. The measurements of the water level elevation at the end of the lock illustrate the importance of this gradual narrowing. An increase of the water level elevation is observed at the end of the lock at a point in time before the ship's bow has reached the entrance. This implies that translation waves are generated at the narrowing between canal and lock section. The narrowing is approximated by introducing intermediary contractions between canal and lock section. At every contraction, translation waves are generated analogous to the generation of translation waves at the lock entrance. This is done by solving Vrijburcht's system resulting again in a Δz_v. A new function has to be introduced: $h_C(x, t, i)$, with i an index corresponding to one of the contractions:

$$h_C(0, t, i) = \Delta z_v \qquad (8)$$

For the calculations at the second intermediary contraction $(i = 2)$, the width at that contraction is conceived as the lock section and the width at the first contraction is conceived as the width of the canal. The generated waves are then added to h_1 once they reach the lock:

$$h_1(0,t) = \sum_i h_C(x(i), t, i) \qquad (9)$$

The parameter $x(i)$ is the distance between the contraction and the actual lock entrance. Due to a better approximation of the narrowing, translation waves are generated earlier and the course of the wave height is smoother.

If the approach channel towards the lock is approximated by the introduction a number of intermediary contractions, the wave is generated earlier and at a higher ship's speed, leading to an improved wave. However, this is not a theoretically perfect solution but an engineering solution leading to improved results. The number of intermediary contractions has to be limited to about 20 for satisfactory results.

The three improvements increase the complexity of the system considerably. A prolonged calculation time is caused by the general for loop for the time and two nested for-loops, respectively for i and x in which Vrijburcht's system has to be solved every time. Still, calculation time is limited to 6 minutes for a typical case with sufficiently small calculation steps.

3.3 CALCULATION OF VERTICAL SHIP MOTIONS

The final goal of the prediction of waves generated by a lock entry is the calculation of vertical ship motions in order to implement this into a ship simulator. The sinkage and trim of the ship are calculated by integrating the changes of the water level over the length of the ship [5]. The water level $\zeta(x,t)$ can be calculated as follows:

$$\zeta(x,t) = \begin{cases} z_k + z_n - h_3(x,t) - h_5(x,t) & \text{if } x > 0 \\ z_k - h_6(x,t) & \text{if } x < 0 \end{cases} \qquad (10)$$

with z_k, the water level depression due to sailing in the canal and z_n the additional reduction of the water level between the bow of the ship and the lock entrance. Once

[1] The wave height is adjusted to the ship's speed. This is not written in the expression for readability reasons.

the water level elevation is known, the sinkage $s(t)$ and trim $\tau(t)$ can be calculated as:

$$s(t) = \frac{\int_{-l_s/2}^{l_s/2} \zeta(x,t) \cdot B(x) dx}{\int_{-l_s/2}^{l_s/2} B(x) dx} \quad (11)$$

$$\tau(t) = \operatorname{atan} \frac{\int_{-l_s/2}^{l_s/2} \zeta(x,t) \cdot B(x) \cdot x \cdot dx}{\int_{-l_s/2}^{l_s/2} B(x) \cdot x^2 \cdot dx} \quad (12)$$

The sinkage and trim allow for the calculation of the position of the bow of the ship at any time, a parameter which is measured during scale model tests.

The calculations can be applied both to the original as the improved six-waves-model. However, the resulting ship motions calculated with the original model are particularly unsatisfying, because according to this model, the ship's bow is not pushed up by the returning translation wave.

4. COMPARISON OF THE CALCULATIONS TO THE MEASUREMENTS

Several relevant measurements are used to verify the results of the hull-adjusted and improved six-waves-model with the empirical results, namely the water level elevation at the end of the lock and the sinkage of the bow. This is done for scale model of a 12000 TEU container carrier and a bulk carrier.

The accuracy of the improved six-waves-model is assessed for these cases; the results are described in the following paragraphs.

4.1 BULK CARRIER SCALE MODEL TEST FOR WEST LOCK TERNEUZEN

The measurements and calculations with the original six-waves-model of the water level elevation at the end of the lock are shown in figure 4 in case of a bulk carrier. The wave height is clearly overestimated and the sudden variations of the water level elevation do not correspond to reality.

The application of the improvements on the six-waves-model eliminates the most important concerns of the original six-waves-model. The improved six-waves-model, combined with a limited empirical optimization, renders better results, as depicted in figure 4. The empirical optimization consists of a reconsideration of the added mass that is taken into account for the calculation of the speed of the ship, an optimization of empirical coefficients, namely the contraction coefficient α is set at 0.9, and minor changes to the celerity of the waves. However, changes to the celerity were not necessary in the case depicted in figure 4.

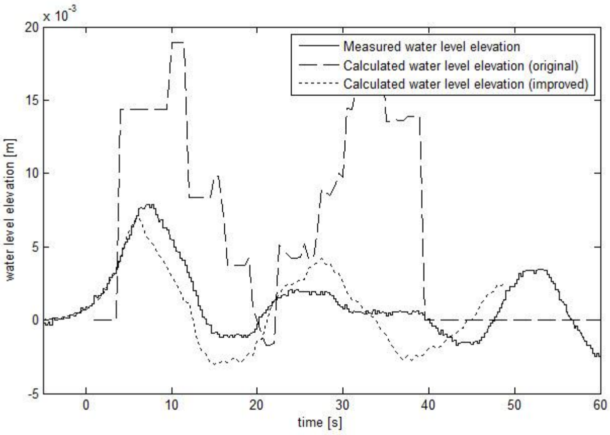

Figure 4: Water level elevation at the end of the lock, measured and calculated with the original and improved six-waves-model. The approach speed is 0.168 m/s.

The usability of the mathematical modelling of translation waves relies on its ability to calculate the vertical movement of the ship. The sinkage of the ship is calculated by integrating the water level elevation alongside the ship. Calculations of the sinkage of the bow are compared to the experimental results. The result for the current case is given in figure 5.

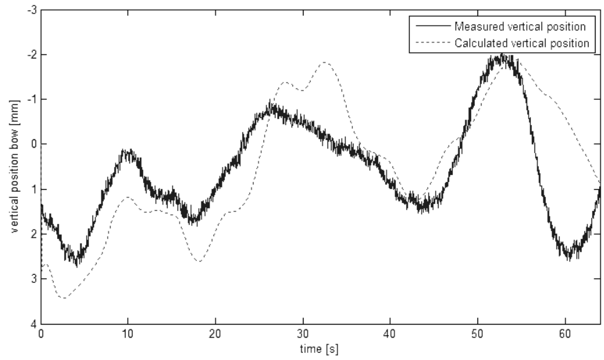

Figure 5: Vertical movement of the bow of the ship, measured and calculated with the improved six-waves-model (30% UKC)

For completeness sake, the calculations with the improved model and the measurements of the speed of the ship are given in figure 6.

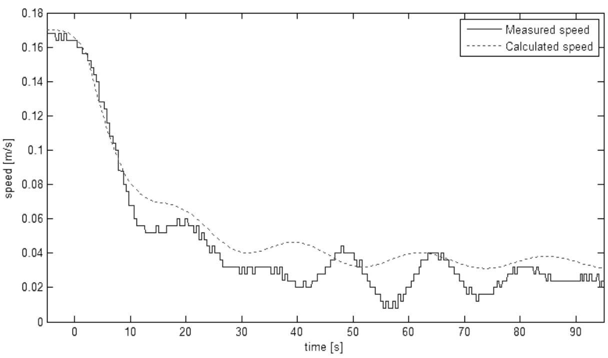

Figure 6: Speed of the ship, measured and calculated with the improved six-waves-model (30% UKC)

4.2 CONTAINER CARRIER SCALE MODEL TEST FOR THE PANAMA CANAL THIRD SET OF LOCKS

In order to assess the effectiveness of the improvements for slender ship's, the results of model scale tests with a container ship are compared to the results with the improved six-waves-model. A container carrier differs more from the original assumptions of the six-waves-model and consequentially the model was less usable for these vessels. The improvements allow for a better modelling and a greater scope of the six-waves-model but the modelling is still less satisfying for a container carrier than for a bulk carrier. Secondary effects have a more important effect on a container vessel than a bulk carrier and the 1D approach has certain limitations that cannot be overcome.

Test case A of the Open model test data in [3] is used here to illustrate the important differences of a lock entrance with a container carrier compared to an entrance with a bulk carrier. In figure 7, the water level elevation is shown calculated both by the original as by the improved model.

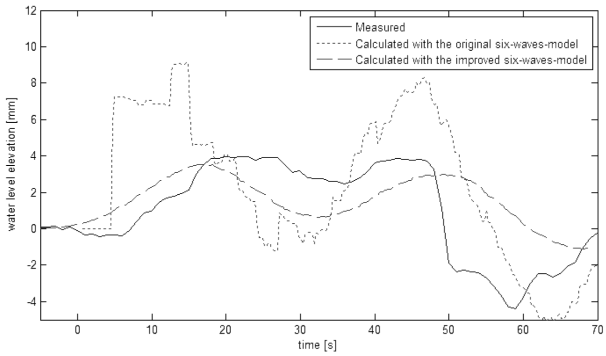

Figure 7: Water level elevation at the end of the lock, measured and calculated with the original and improved six-waves-model (20% UKC, water height, 0.23m)

The water level elevation lacks the regularity that was found empirically for the entry of a bulk carrier. The wave is generated more gently. This is a tendency that is also found in the improved modelling, but not that pronounced as observed empirically. After 50 seconds, the speed of the container carrier falls rapidly, resulting in a steep fall of the water level (see figure 8). Here, the modelling is not very successful. However, the model is improved to enhance the results especially during the first phase of the entry.

The calculation of the sinkage of the bow is particularly less satisfying for the container vessel than the bulk carrier but nevertheless greatly improved compared to the results of the original model (see figure 9). A bow-down trim is predicted by the original model, contrary to

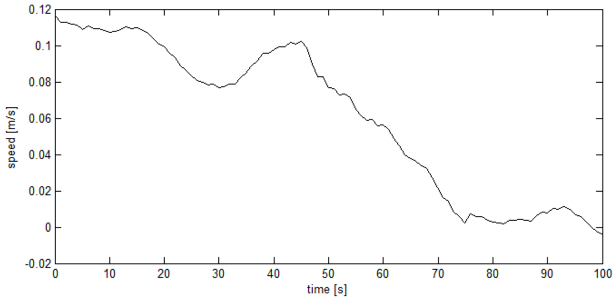

Figure 8: Measured speed of the ship during entrance (20% UKC, water height, 0.23m)

the predictions of both the improved model and empirical observations with the container carrier. The tendency of the sinkage of the bow as calculated with the improved model is relatively accurate, the bow of the ship first sinks in the water, and is pushed up once the reflected translation wave reaches the ship. However, the magnitude of the sinkage is quite sensitive to an empirical factor of Vrijburcht's system, and to ship's speed (the results here are calculated with the measured ship's speed, contrary to the calculations for a bulk carrier).

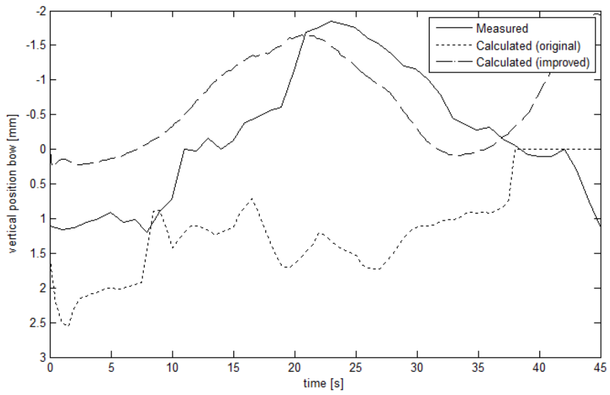

Figure 9: Vertical movement of the ship's bow, measured and calculated with the improved six-waves-model (20% UKC).

4.3 FULL SCALE LOCK ENTRANCE IN THE PORT OF DUNKIRK (DUNKERQUE)

On the 5th of December 2012 Flanders Hydraulics Research (FHR) performed a survey on the MV Cape Aster departing from the Western port of Dunkirk at 11:00 am and mooring to the Arcelor Mittal plant in the Eastern port of Dunkirk at 08:30pm (see [6]). The survey was carried out in order to analyse the ship behaviour during the passing of the Charles de Gaulle Lock in the Eastern port of Dunkirk. The measurements of the ship movements can be used to verify the improvements to the mathematical model as described above. The MV Cape Aster is a cape size bulk carrier (292 m x 45 m x 14.2 m). The underkeel clearance in the lock equals 28.2%.

Table 2: Main dimensions full scale test

Main dimensions Charles de Gaulle lock	
Lock width	50m
Lock length	364m
Water height	18.21m
Main dimensions MV Cape Aster	
Ship beam	45m
Ship length over all	292m
Draught	14.2m

A full scale lock entrance will exhibit some differences from the model scale tests. A number of environmental factors have effects on real entrances which are not accounted for in the model scale tests or the mathematical model, for instance: wind effects, forces exerted by the tugs or manoeuvres before entering the lock. In this case, the ship's heading changed about 180° from the sea to the entrance of the lock (figure 10), with very important hydrodynamic effects. According to [6], the effects of the turning disappeared before the lock entrance began.

The calculation of the vertical position of the bow during the lock entrance is calculated similarly as the previous cases, but for this case on full scale. The empirical and calculated results are shown in figure 11. The empirical coefficients are optimized, namely by setting $\alpha = 1.2$.

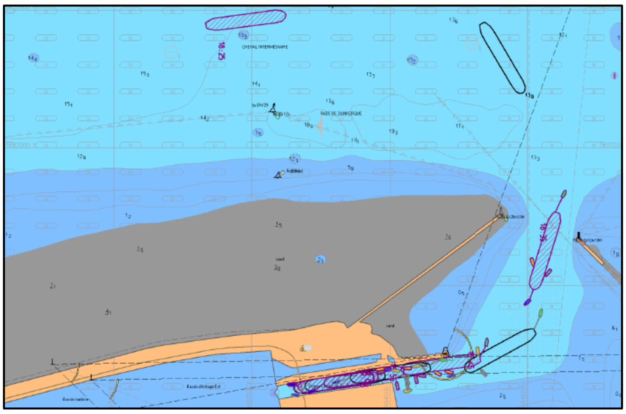

Figure 10: Manoeuvre made by the MV Cape Aster, entering the Charles De Gaulle Lock

One of the parameters, the width of the approach channel b_k, is difficult to choose, since the lock has no real approach channel, the ship sails in coming from the sea immediately (see figure 10). However, the guiding structure has an influence as illustrated by the previous examples on model scale. The width between the guiding structure and the landward end of the basin is minimally $b_k = 300$m, which is used as the channel's width.
The calculated movements are less pronounced than in reality. In the measurements, short period fluctuations occur that cannot be explained by the mathematical modelling. However, the general tendency of the measurements and calculations is similar, especially from 400 seconds after lock entrance onwards.

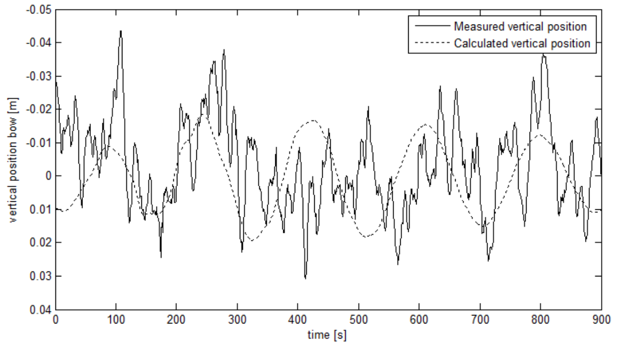

Figure 11: Vertical movement of the ship's bow, measured and calculated with the improved six-waves-model (28% UKC).

The calculation of the speed is an important factor for the full scale test runs, since the lock entrance causes important hydrodynamic and resistance forces which have to be overcome by tug boat assistance combined with the propulsion of the ship. The mathematical model uses a 1D approach, so only longitudinal forces and speed are calculated. In order to calculate the speed, the total longitudinal thrust has to be known, both caused by the propulsion of the ship and by the tug boats. The thrust of the tug boats are measured in the full scale test and the longitudinal component of the thrust is calculated. A constant propeller rate of 36 rpm according to engine order dead slow ahead was maintained during the lock entrance until the ship entered the lock for 220m (after about 455s).

Figure 12 shows the evolutions of both the measured and calculated ship's speed during the ship entry into the lock. The results are generally satisfying, although sudden changes in the speed further in the lock are not seen in the calculations.

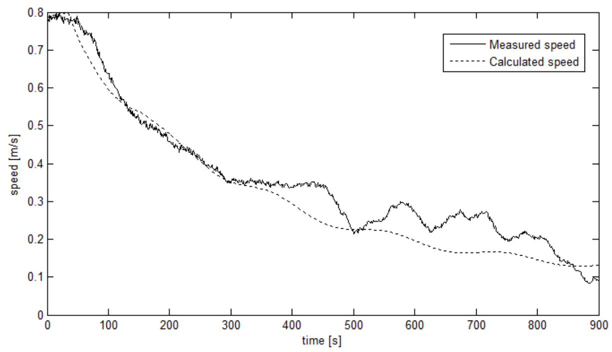

Figure 12: Ship's speed, measured and calculated with the improved six-waves-model (28% UKC).

4. IMPLEMENTATION OF THE MODEL IN A SHIP SIMULATOR

Up to this point, all calculations were carried out by the numerical computing environment MATLAB 7.10.0 (R2010.a). This was proven useful to analyse the ruling phenomena and to implement adjustments to the model accordingly. The ultimate goal, however, is to implement this model in a ship simulator and to combine this model with all possible variables that are already implemented. The current ship simulators at Flanders Hydraulics Research use the original six-waves-model of Vrijburcht.

5. FURTHER STUDY

A further study of the six-waves-model should be focused on a refinement of the system of Vrijburcht. The system is necessarily approximate because of the assumptions and the absence of partial differential equations but has proven to have potential.

A number of phenomena that were pointed out during the comparison between measurements and calculations can be examined in more depth. In particular the irregular behaviour of the translation waves and the ship's motion cannot be explained by the present theoretical model. Consideration of secondary effects and changes to the theoretical approach may be in order. The effect of ship motions on the generation of translation waves is not taken into account in the present work. A more accurate model could be construed, accounting for the bow-up trim of a container vessel in the canal on the one hand and considering the bow-down trim of a bulk carrier on the other hand.

In this work, the majority of the tests are carried out with a bulk carrier. Additional testing of container vessels, in particular less extreme cases with a constant thrust and reasonable under keel clearances could render better and more reliable results. This would allow for a breakdown of several phenomena that cause less satisfying results for container vessels than bulk carriers. Since translation waves are less pronounced for container carriers, both according to measurements as calculations, secondary effects are relatively more important. If a considerably higher level of complexity would be allowed, a 2D or 3D approach could be used in order to get more accurate results.

6. CONCLUSIONS

The hydrodynamic effects that occur during the entrance of a ship in a lock are assessed empirically and an improvement to the mathematical modelling as used by Flanders Hydraulics Research (the six-waves-model) was undertaken.

The 1D approach of Vrijburcht can be used effectively to model translation waves in locks. By compensating a number of assumptions of the six-waves-model, as proposed here, the scope of the model can be increased significantly. The calculated translation waves are smoother and more realistic by considering the hull shape and the geometry of the lock entrance. The improved model is a typical engineering solution based on both a theoretical approach and pragmatic compensations for the necessary assumptions.

The improved model could be especially useful for rather full sea-going ships in locks with only limited side and under keel clearance. The work was originally carried out with model-scale test results only. An isolated use of the model does not lead to satisfactory results for real scale lock entrances. It only accounts for the 1D hydrodynamic effects of the lock entrance, wind effects, lateral forces, movements due to previous manoeuvres, etc. are not taken into account. In a ship simulator, all these effects are accounted for, the mathematical model discussed in this work is only one small piece of the puzzle. More work has to be done to make the model appropriate for slender ships.

Due to the transparency of the six-waves-model and the effectiveness of the improvements, some empirical observations were also highlighted. For instance, the effect of the shape of the bow has a very important influence on the magnitude of the translation waves. Another, less anticipated, observation was the effect of the shape of the approach channel on the translation waves and the vertical movements of the ship. If the cross-section of the channel narrows gradually over a certain length towards the lock, then the translation wave is also generated more gradually by the lock entrance.

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